Updating a Land Surface Model with MODIS-Derived Snow Cover

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ABSTRACT

A simple scheme for updating snow-water storage in a land surface model using snow cover observations is presented. The scheme makes use of snow cover observations retrieved from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard NASA's *Terra* and *Aqua* satellites. Simulated snow-water equivalent is adjusted when and where the model and MODIS observation differ, following an internal accounting of the observation quality, by either removing the simulated snow or adding a thin layer. The scheme is tested in a 101-day global simulation of the Mosaic land surface model driven by the NASA/NOAA Global Land Data Assimilation System. Output from this simulation is compared to that from a control (not updated) simulation, and both are assessed using a conventional snow cover product and data from ground-based observation networks over the continental United States. In general, output from the updated simulation displays more accurate snow coverage and compares more favorably with in situ snow time series. Both the control and updated simulations have serious deficiencies on occasion and in certain areas when and where the precipitation and/or surface air temperature forcing inputs are unrealistic, particularly in mountainous regions. Suggestions for developing a more sophisticated updating scheme are presented.

1. Introduction

In middle- to high-latitude and alpine regions, the seasonal snowpack can dominate the surface energy and water budgets because of its high albedo, substantial heat capacity and insulating properties, and ability to store and then quickly release a winter's worth of precipitation. Furthermore, scientists have recently identified teleconnections between the snowpack in certain regions and subsequent meteorological conditions in other regions. Bamzai and Shukla (1999) used satellite- and ground-based observations to confirm a previously inferred inverse relationship between winter snow cover over western Eurasia and subsequent Indian summer monsoon rainfall. Several observation-based studies have shown that Eurasian snow cover influences the state and persistence of the Arctic Oscillation (Cohen and Entekhabi 1999, 2001; Bojariu and Gimeno 2003; Saito and Cohen 2003; Saunders et al. 2003), which in turn affects the severity of the winter season in the entire Northern Hemisphere. Similarly, Gong et al. (2002, 2003) used atmospheric models to demonstrate that Siberian snow perturbations modulate the Arctic Oscillation. Thus the accurate representation of snow cover is crucial to numerical weather prediction models for producing reliable daily to seasonal forecasts, yet these models often have difficulty simulating snow cover and water storage during times of accumulation and ablation (Foster et al. 1996). Dependable snow data are also critical for flood preparedness and water management applications as well as for developing a comprehensive understanding of the global hydrological cycle.

The Moderate Resolution Imaging Spectroradiometer (MODIS) instruments (Justice et al. 1998) on the National Aeronautics and Space Administration's (NASA's) *Terra* and *Aqua* satellites are now providing high-resolution daily observations of snow cover. However, this snow cover information simply stipulates the presence or absence of snow, as opposed to snow-water equivalent (or depth) information, which actually quantifies the snowpack. The latter is more desirable for most applications and water budget studies. Furthermore, MODIS can neither "see" through clouds nor make observations at night. Therefore MODIS observations alone are unsatisfactory for forecasting applications.

Incorporating satellite-based snow observations into sophisticated land surface models (LSMs), which provide spatial and temporal continuity and also quantify the snowpack, may be the key to producing accurate, high-resolution maps of snow-water equivalent in near–real time. LSMs provide spatial and temporal continuity and also quantify the snow water storage, but the quality of their output is limited by the quality of the input forcing data and the simplifications necessary to simulate complex physical processes economically. This is the premise behind data assimilation. The following sections describe

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the development and testing of a simple algorithm for updating a global, high-resolution land surface model with snow cover data derived from MODIS observations. The goal is to improve the simulation of snow in an LSM despite the shortcomings of the model's snow formulation and the atmospheric forcing data.

2. Background

a. Mosaic

Mosaic (Koster and Suarez 1992) is a well-established LSM with roots in the Simple Biosphere model of Sellers et al. (1986). When it was developed, the primary innovation of Mosaic was its treatment of subgrid-scale variability. It divides each model grid cell into a mosaic of tiles (after Avissar and Pielke 1989) based on the distribution of vegetation types within the cell. Each tile represents one vegetation class and is weighted by the cell fraction of vegetation in that class. Tiles are modeled as independent soil columns, and therefore do not interact with each other directly. Each tile has three soil layers, and surface flux calculations are similar to those described by Sellers et al. (1986).

Mosaic includes a single-layer snow formulation based on a simple water balance:

$$S_{\text{new}} = S_{\text{old}} + (P_S - S_{\text{melt}} - E_{\text{snow}})\Delta t, \qquad (1)$$

where S is water equivalent in the snowpack, P_S is snowfall rate, S_{melt} is rate of snowmelt, E_{snow} is snow sublimation rate, and Δt = change in time. Snowmelt rate is computed based on the residual from the surface energy balance equation and continues until no snow remains or the ground temperature is reduced to freezing. Similarly, if the ground temperature is above freezing when snow falls, that snow melts immediately and the ground temperature is reduced accordingly. When at least 5-mm snow-water equivalent is present, it modifies the surface albedo and thus influences the surface energy balance calculations. Above 25 mm only snow albedo is considered.

This snow formulation is very simple and is not as realistic as those included in certain other modern land surface models. In particular, the evolution of the snowpack, including compaction, heat storage, and liquid water storage, is not considered. If snow is present when rain falls, it is simply ignored while the rainwater is partitioned into canopy interception, infiltration, and runoff. Nevertheless, these flaws do not diminish the value of this study because the goal is not to produce a perfect result, but rather to show that snow cover observations from MODIS can be used to improve the simulation of snow in an LSM despite its shortcomings.

b. GLDAS

The Global Land Data Assimilation System (GLDAS) was developed through a joint NASA and National Oceanic and Atmospheric Administration (NOAA) endeavor, with the goal of integrating satellite- and ground-based observational data products in order to generate optimal fields of land surface states and fluxes (Rodell et al. 2004). GLDAS drives multiple, uncoupled LSMs, including Mosaic, globally at high resolution (0.25°), producing both retrospective and near–real time output. GLDAS has incorporated the Mosaic subgrid tiling approach into its main driver, with a 1-km global vegetation dataset as its basis. GLDAS enables the models to be forced by observation-based precipitation and downward radiation fields as well as output from global coupled atmospheric data assimilation systems. Soil and elevation parameters are based on high-resolution global datasets, and the elevation data are used to adjust the temperature, humidity, pressure, and longwave radiation forcing fields. Various techniques for constraining the LSMs with satellite-derived data are being explored and implemented, including the snow updating algorithm described here.

c. MODIS-derived snow cover

This study made use of the daily, 0.05°-resolution MODIS climate-modeling grid-level-3 product (MOD10C1), which is based on 500-m *Terra*/MODIS observations (Hall et al. 2002). MOD10C1 specifies the fraction of each 0.05° grid cell that was observed to be snow covered, the fraction that was cloud covered, and the fraction (known as the ''confidence index'') in which the land surface was visible (i.e., not obscured by clouds, night, or otherwise), at the time of the satellite overpass (approximately 10:30 A.M. local time).

Bitner et al. (2002) compared the National Operational Hydrologic Remote Sensing Center's (NOHRSC) daily satellite-derived 1-km snow cover maps (for the coterminous United States and Alaska) with automated snow cover maps produced by the National Environmental Satellite, Data, and Information Service (NESDIS; 5 km) and with 500-m MODIS-derived snow cover maps. The NESDIS maps showed 96% agreement with NOHRSC for sample areas in the Pacific Northwest and Great Plains, and the MODIS maps showed 94% and 95% agreement in those areas. These three products rely on data from different sensors at different resolutions, so intercomparison can be considered a form of validation.

Maurer et al. (2003) compared the 500-m daily MODIS product with the 1-km NOHRSC product, using ground-based observations for validation, over the Columbia and Missouri River basins for selected days during the winter of 2000/01. They determined that MODIS classified fewer pixels as cloud (i.e., more were classified as snow covered or bare ground), and of the pixels classified as cloud free, the MODIS product misinterpreted the existence of snow 4%–5% less often than the NOHRSC product.

d. Observation-based snow products

Several snow products based on satellite and ground observations of snow cover are now available. In addition to MODIS, satellite sensors capable of observing snow are on board polar-orbiting and geostationary platforms including Defense Mapping Satellite Program and Geostationary Operational Environmental Satellite (GOES) weather satellites. Ground-based observations include snow-water equivalent measurements recorded at over 600 automated snowpack telemetry (SNOTEL) stations throughout the western United States and by thousands of volunteers in the U.S. National Weather Service Cooperative Observer Program (referred to here as Co-op). NOAA's MultiSensor Snow and Ice Mapping System (IMS) incorporates observations from multiple satellites, measurement networks, and additional sources to produce global, daily, 25-km snow cover maps (Ramsay 1998). The snow cover product of the National Weather Service's NOHRSC also is based on data from multiple sources and is produced daily at a 1-km resolution for the conterminous United States (Hartman et al. 1995). Daily 5-km snow cover maps based on GOES and Special Sensor Microwave Imager (SSM/I) data are produced by NESDIS (Bitner et al. 2002).

e. Snow data assimilation

In concept, assimilating snow observations improves the land surface model's realism by retaining superior qualities of the model and observations, while minimizing errors. For example, models have the advantage of being spatially and temporally continuous, and they account for the snow-depth or -water equivalent, while most remote snow observations only provide snow cover information. On the other hand, observations generally are less biased than model estimates. Thus, through data assimilation, a superior (less error and bias), temporally and spatially continuous estimate of various snowpack properties can be attained using scattered observations.

Nevertheless, only a handful of studies have considered the assimilation of snow observations in an LSM. Most directly replaced the modeled snow states with the observations (e.g., Liston et al. 1999), while a few have tested more complex schemes. Wilson et al. (1999) compared hydrology model–estimated brightness temperatures with SSM/I observations and used the differences to update the modeled snow parameters. Chen et al. (2001) improved upon this approach by implementing a neural network for the parameter inversion. Guo et al. (2003) later applied the approach for spatially distributed snow mapping and demonstrated improvements in estimated snow parameters over the upper Rio Grande basin in Colorado based on comparisons with SNOTEL observations.

Brasnett (1999) used a data assimilation method known as statistical interpolation to assimilate snow-depth observations from synoptic stations. He used a simple snow accumulation, aging, and melt model driven by forecasts of precipitation from a numerical weather prediction model and analyses of screen-level temperature to produce the first-guess field. The resultant global analysis of snow depth was shown to be more faithful than the climatology for the study period. Brown et al. (2003) applied the method of Brasnett (1999) to generate a gridded monthly dataset of snow depth and snow-water equivalent over North America, using snow depth observations from the U.S. Co-op stations and Canadian climate stations. They showed that the gridded results agreed well with in situ and satellite data over midlatitudes during the second Atmospheric Model Intercomparison Project (AMIP II) period (1979–96).

Cosgrove and Houser (2002) studied the effect that snow data assimilation has on the water balance of an LSM with prescribed biases. Identical twin simulations were conducted for central North America using the Mosaic LSM over the 12-month period covering October 1998 to September 1999. Snow data from a control simulation were directly inserted into experimental runs featuring temperature biases of $\pm 1°C$ and solar radiation biases of $\pm 10\%$. Results revealed that the interaction of such model biases with direct insertion of snow data led to large assimilation flux biases over much of the region, which were comparable to a 9%–30% increase in yearly precipitation over much of the Rocky Mountains and eastern Canada. Subsequent experiments demonstrated that this effect could be mitigated by adjusting the freezing-point temperature whenever the snow was updated in order to slow the model drift back toward the preupdated state.

Sun et al. (2004, manuscript submitted to *J. Geophys. Res.*) developed a more sophisticated scheme that assimilates snow-water equivalent observations efficiently into the NASA Seasonal-to-Interannual Prediction Project (NSIPP) Catchment LSM, using the extended Kalman filter and taking into account the evolution of the model error covariances. Twin experiments illustrated that by assimilating snow-water-equivalent observations from remote sensing satellites, the modeled snow field quickly evolved from an inaccurate initial condition to a realistic one, and the modeled runoff and atmospheric fluxes improved.

Additional snow assimilating models include the U.S. Air Force Weather Agency's (AFWA) Agricultural Meteorological modeling system, which incorporates SSM/I and ground observations. NOHRSC is also developing a Snow Data Assimilation System (SNODAS) that will run daily for the coterminous United States (Carroll et al. 2001). At the core of SNODAS is a physically based energy-and-mass-balance snow accumulation and ablation model. The model is forced by downscaled analysis and forecast fields from a mesoscale numerical weather prediction model [20-km Rapid Update Cycle (RUC20)] surface weather observations, satellite-derived solar radiation data, and radar-derived precipitation data. The simulated

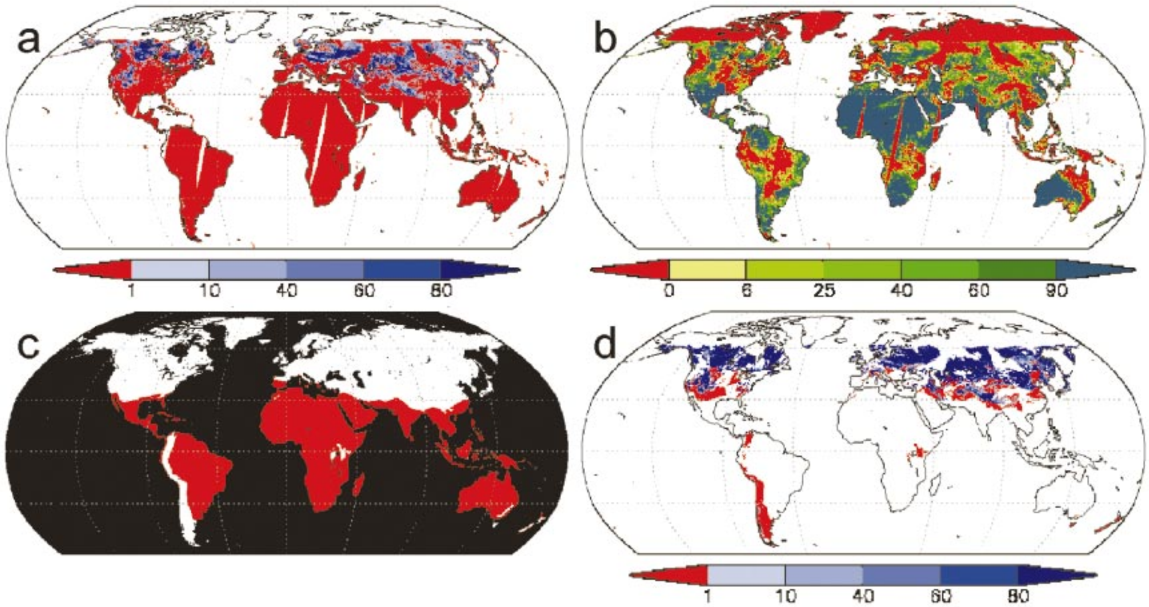

FIG. 1. For 1 Jan 2003: (a) MOD10C1 snow cover (%); (b) MOD10C1 confidence index (% visible pixels); (c) snow-impossible mask (red indicates snow impossible regions); and (d) ''enhanced MODIS snow cover'' (%).

snow model state variables are updated using satellite, airborne, and ground-based snow observations.

3. Methods

A scheme for incorporating information from global MOD10C1 snow cover fields, described above, into GLDAS/Mosaic simulations was designed, tested, and refined. A global MOD10C1 field is read at the beginning of each model day, but individual grid squares are updated only when the local time is 10:30 A.M., to approximate the time of the *Terra* satellite overpass. The scheme assesses, on a point by point basis, the reliability of the MODIS observation and the likelihood that snow cover exists, and adjusts the modeled snow states accordingly. For this study the 0.05° MOD10C1 data were preprocessed by binning up to 0.25° to match the GLDAS grid.

The reliability of a MODIS snow cover observation (Fig. 1a) within a given grid square is determined based on the MOD10C1 confidence index (Fig. 1b). MODIS cannot ''see'' through clouds, but clouds are often pervasive where snow exists, so it is essential to make prudent use of data from grid squares that are partially cloud covered, in order to avoid squandering useful information. Taking this reasoning into account and based on a visual assessment of the credibility of the observed snow cover state at varying levels of the confidence index, it was decided that 6% is the minimum visibility for which an observation is useful. This parameter can easily be adjusted if a more appropriate value is later identified, but 6% is an adequate starting point. Further, a snow-impossible mask (Fig. 1c) is applied to prevent snow cover from being added to, for example, Cuba, where MODIS occasionally mistakes sand for snow. If the confidence index is at least 6% in a snow-possible grid square, then the percentage of visible, snow-covered 500-m pixels is divided by the confidence index to establish the fraction of ground-visible (cloud free) pixels that were snow covered. The resulting field is referred to hereafter as enhanced MODIS snow cover (Fig. 1d).

For each grid square at 10:30 A.M. local time, the enhanced MODIS snow cover is compared to the modeled snow-water equivalent variable and the latter is adjusted if there is a discrepancy, as follows. If the LSM does not have snow but the enhanced MODIS snow cover is greater than 40%, then a nominal layer of snow is added in the LSM. For this study, 5-mm equivalent height of water was chosen as the amount of snow to add because of the desire to minimize the assimilation flux as a contribution to the water balance while still affecting the albedo. If the model has snow but the enhanced MODIS snow cover is less than 10%, then the modeled snow water equivalent is set to zero. In cases where the model and observation agree or the enhanced MODIS snow cover is between 10% and 40%, the modeled snow-water equivalent is unchanged. These intervals were chosen based on the desire to balance quality control (ignoring spurious observations) with information retention (not wasting valid observations).

It is well accepted that sophisticated data assimilation methods based on Kalman filtering or variational approaches produce more optimal results than updating (e.g., Walker et al. 2003). However, these approaches generally rely on the existence of a continuous rela-

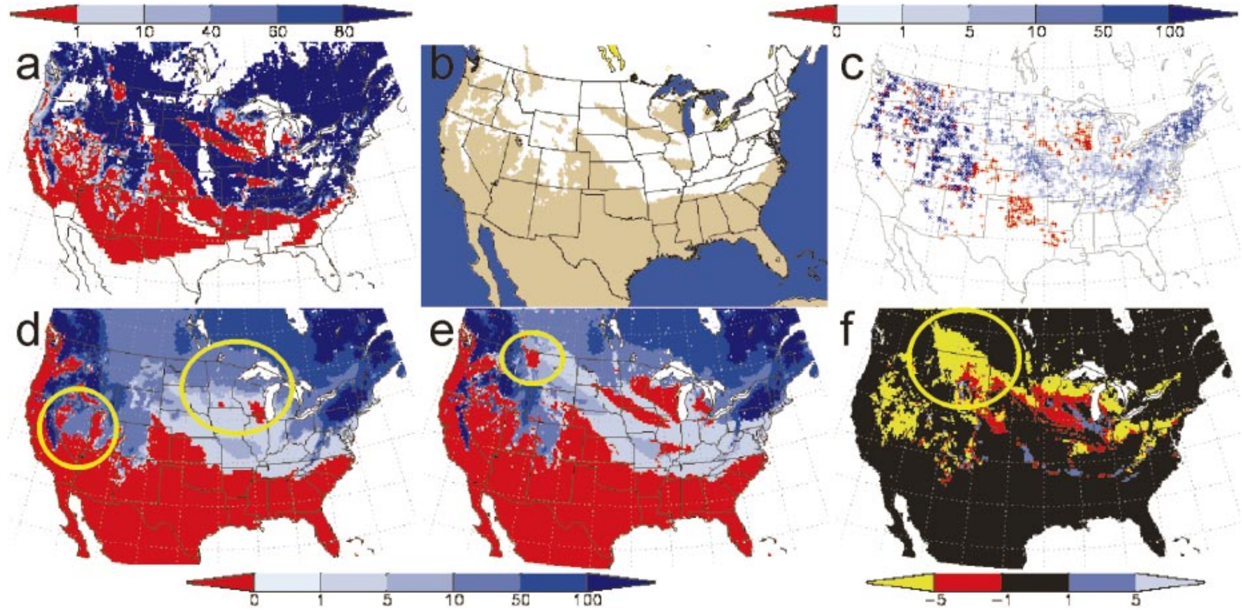

FIG. 2. For 17 Jan 2003 over central North America: (a) enhanced MODIS snow cover (%); (b) IMS snow cover (white = snow); (c) SNOTEL (X's) and estimated Co-op (crosses) snow-water equivalent (mm); (d) control run GLDAS/Mosaic snow-water equivalent (mm); (e) assimilated GLDAS/Mosaic snow-water equivalent (mm); (f) difference between assimilated and control run GLDAS/Mosaic snow-water equivalent (mm). Yellow circles guide reader's eyes to areas of interest mentioned in the results section.

tionship between the model's states and the observations. Unfortunately, snow cover observations are related in a noncontinuous, threshold fashion to the model states; the presence of snow cover indicates that there is some snow-water equivalent, but gives no indication as to how much snow-water equivalent exists. Because of this threshold relationship, the ''rule based'' snow cover updating assimilation scheme described above was developed for this study.

4. Results

a. Spatial analysis

Results are presented from a 101-day Mosaic simulation (1 January to 11 April 2003) in which the snow field was adjusted each day based on the MODIS data, and from a control simulation in which no updates were made. The simulations were driven by GLDAS at 0.25°-resolution globally, forced by output from the Goddard Earth Observing System (GEOS) atmospheric data assimilation system (Pfaendtner et al. 1995) adjusted to the elevations of the 0.25° GLDAS grid. Improvements in the updated snow fields as well as shortcomings of the technique can be seen in Figs. 2–5, which compare enhanced MODIS snow cover and Mosaic output for the control and snow update simulations with the IMS snow cover product and Co-op and SNOTEL observations over the continental United States on 4 days of interest.

The best MODIS observation over this region and period of study occurred on 17 January. As shown in Fig. 2a, the scene is nearly complete and closely matches the IMS snow cover map and ground-based observations (Figs. 2b and 2c). The control simulation (Fig. 2d) put snow in many areas where it should not have been and not enough snow in other areas (Fig. 2f), while the updated model was able to be set to a nearly perfect state in terms of snow extent (Fig. 2e).

In contrast, the MODIS scene on 6 February is largely incomplete over the central and eastern United States (Fig. 3a). A major snow storm was crossing the central United States on that day. Unfortunately, the same clouds that bring snow also obscure the land surface from visible-wavelength satellite observations. As a result, any inaccuracies in the modeled snow extent can only be corrected after the sky has cleared. It is unknown how precisely the progression of that snow storm was simulated since the ground-based observations (Fig. 3c) and IMS field (Fig. 3b) do not provide subdaily information. MODIS also was unable to verify or refute a snowfall event centered on western Texas that was simulated by the models on 7 February (Fig. 4d). Because of inadequate station coverage in that region, a reliable satellite observation would have been valuable. Figure 3a reveals another feature of the MOD10C1 product and the method used here to enhance it: the edges of clouds are sometimes misinterpreted as snow cover, as seen in the southeastern United States. In this case the model did not allow the erroneously added snow to persist (Fig. 3e), which demonstrates one advantage of data assimilation over observation alone.

The updating scheme produced decreases in modeled

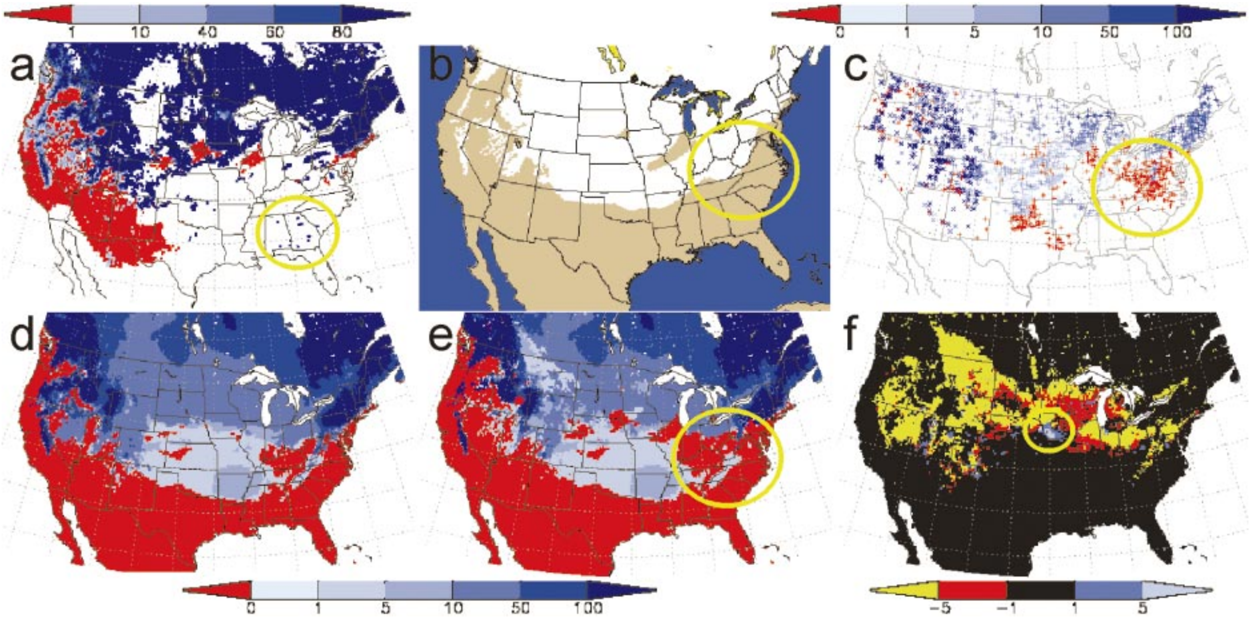

FIG. 3. Same as Fig. 2, but for 6 Feb 2003.

snow-water equivalent in many locations and increases in others. Updates in early January caused a reduction of snow depth in Montana and neighboring areas that persisted through the rest of the snow season (Figs. 2f, 3f, 4f, and 5f). Holes in the snow cover in Montana on 17 January and 12 February (Figs. 2e and 5e) are corroborated by the IMS product, but validating snow-water equivalent is more complicated (comparisons with station data are examined in the next section). The updated simulation also had consistently more realistic snow coverage in Nevada than the control, which predicted continuous seasonal snow cover over much of the state. More accurate delineations of ephemeral snow cover owing to removal by the updating scheme occurred in many other instances, such as over central Arkansas and northern Illinois on 7 February (Fig. 4).

An example in which the scheme successfully added a layer of snow is shown in Fig. 5 in south-central Illinois and southern Indiana. Also note that the MODIS and ground-based observations confirm the snow-free

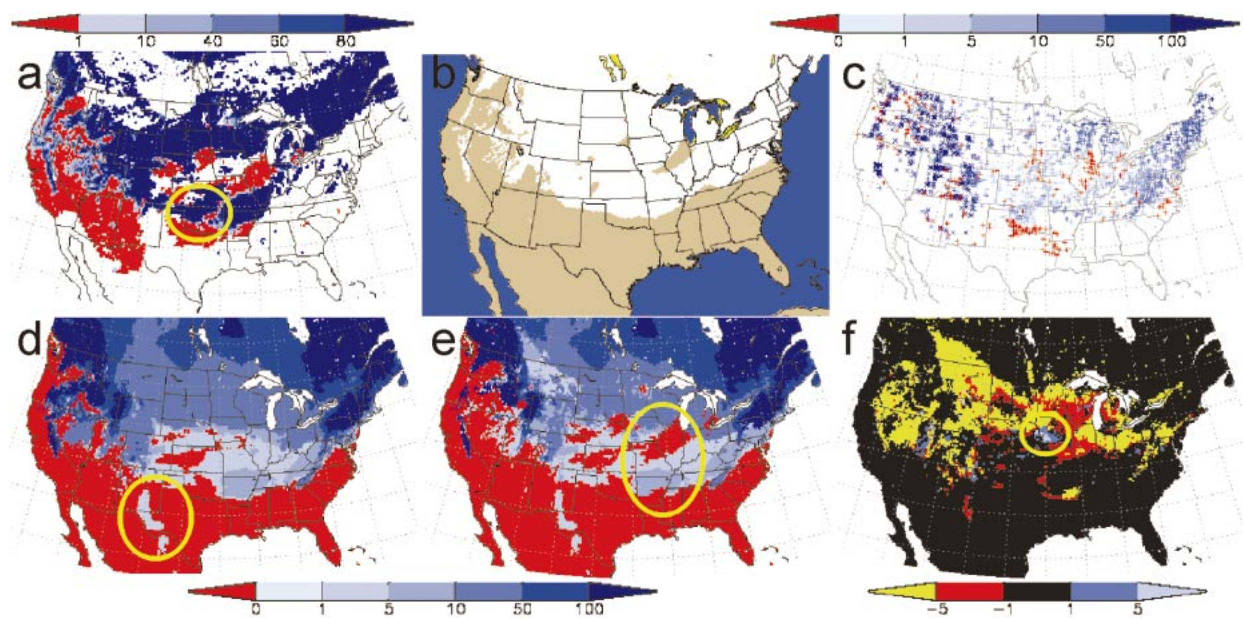

FIG. 4. Same as Fig. 2, but for 7 Feb 2003.

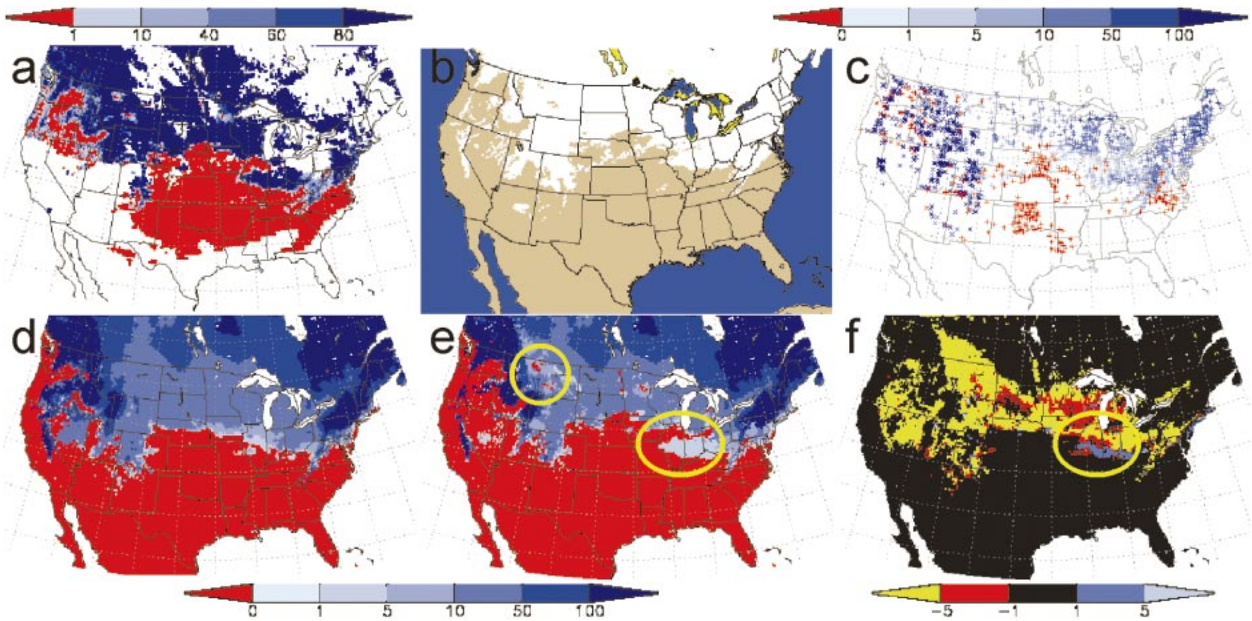

FIG. 5. Same as Fig. 2, but for 12 Feb 2003.

extent in the updated run in north-central Illinois and northern Missouri on that day, while the IMS assigned broader snow coverage. However, the snow added by the updating scheme often melted immediately. On 7 February, MODIS provided a clear view of snow covering most of Oklahoma (Fig. 4a), but that was not reflected in the model a few hours later because the temperature was too warm to sustain the 5-mm water equivalent of snow added by the updating scheme. On other occasions, the added snow enabled subsequent simulated snowfall to accumulate rather than melt immediately. This is apparent in southwestern Iowa, where an increase in snow-water equivalent greater than 5 mm (i.e., more than the quantity of snow added) persisted in the updated simulation from 30 January to 11 February (Figs. 3f and 4f). In that instance Co-op station data generally supported the greater snow amounts.

TABLE 1. List of weather stations from which observations are plotted in Fig. 6.

Figure	Site name, state	Lat (°N)	Lon (°W)	Elev (m)
6a	Spokane, WA	47.68	117.63	796
6b	Chinook, MT	48.58	109.23	715
6c	Riverton, WY	43.02	108.38	1509
6d	Glade Park, CO	38.95	109.05	2070*
6e	Rice Park, NM	35.23	108.27	2579
6f	Shenandoah, IA	40.78	95.35	296
6g	Willow Springs, IL	41.70	87.85	218*
	Burbank, IL	41.73	87.77	190*
	New Lenox, IL	41.53	87.94	230*
6h	Winamac, IN	41.02	86.58	210
	North Judson, IN	41.22	86.72	215
6i	Dale Enterprise, VA	38.45	78.93	427
6j	New Brunswick, NJ	40.47	74.43	26
	Freehold, NJ	40.31	74.25	59

* Estimated elevation.

b. *Time series analysis*

As a second form of validation, time series of control and updated model output were plotted beside daily observations from stations (Table 1) within the given grid squares, in order to assess the accuracy of the simulated snow water equivalent (Fig. 6). Snow-water equivalent was estimated as 10% of the Co-op-measured snow depth, which is an acceptable though by no means perfect approximation (e.g., Dingman 1994). Ten locations were chosen to illustrate a variety of different outcomes of the updating scheme, in particular those that differ from the control, but these are not necessarily representative of all outcomes. The comparisons should be viewed with a healthy skepticism because snow-depth or -water equivalent is likely to be highly variable within a 0.25° grid square, so that validation by point measurements is far from ideal, especially when only one or at most three sets of data are available. Nonetheless this exercise provides useful information on the model's ability to simulate the timing of snowfall and snowmelt and the approximate depth of the snowpack.

Figure 6a (southeastern Washington) exemplifies a common situation in which the model allowed the snowpack to accumulate unabated to unrealistic depths, presumably because the temperature never rose above freezing. In this case the updating scheme correctly removed the entire snowpack on 7 January and continued to keep it in check. Based on the Co-op observations the resulting updated simulation appears to be much more accurate.

Figure 6b (north-central Montana) shows the updating scheme working at its finest. While the control run again had problems with excessive snow accumulation, the updating scheme periodically reset the snow-water equivalent to zero. The resulting model output is remarkably faithful to the observations.

Figure 6c (central Wyoming) demonstrates that the updating scheme can also effect an increase in snow-water equivalent. The modeled snow water amounts and timing of events seem reasonable for both simulations (the updated simulation may be slightly better) in comparison to the observations, taking into account that a single point measurement provides an imperfect sampling. On 19 February, the updates begin to increase the snow water equivalent, despite its being greater than 1 mm (snow is only supposed to be added if the model has less than 1 mm). The explanation is that the subgrid tiles are updated individually, while only the areally weighted average of each grid square's tiles is output. In this case snow was added to tiles with less than 1-mm snow water equivalent, increasing the average, which included tiles with more.

In Fig. 6d (west-central Colorado), it is apparent that the model has again allowed too much snow to accumulate. Oddly, the updating scheme removed all snow on 2 February, when a major snowfall event evidently occurred, while the control run, with only a slight increase on that day, matched the subsequent observed snow water equivalent almost exactly. From 15 February forward the updated run performed significantly better than the control run, though it was still far from perfect.

The only comparison with a SNOTEL time series is shown in Fig. 6e (west-central New Mexico). As is normally the case with SNOTEL sites, this one is at a high elevation (2579 m), and the seasonal snowpack becomes very deep (160-mm water equivalent on 4 March). However, the average elevation of the encompassing 0.25° model grid square is considerably lower (2431 m). As temperature decreases with elevation, this may explain, at least in part, why the simulations have much less snow accumulation. The updated run is even worse than the control in this case, due to the periodic removal of the snowpack. It is quite possible that much of that 0.25° grid square was truly snow free at times, so that the MODIS observations rightly triggered snow removal. Comparisons with other SNOTEL time series are not presented because at most locations not typified by Fig. 6e, snow cover was continuous throughout the period of the run, and hence the control and updated simulations did not differ.

Figure 6f (southwestern Iowa) displays another example in which the updates caused a significant, though temporary, increase in the modeled snow-water equivalent. In this case neither output time series corresponds particularly well to the ground observations. A significant snowfall that occurred on 19 and 20 March was completely missed by the models. Thus, snow cover data assimilation does not eliminate the need for good input forcing.

Three active observation stations were located in the grid square for which data are depicted in Fig. 6g (northeastern Illinois). The variability in snow depth and timing among the three sites underscores the complexity of trying to represent natural snow-water storage using even a relatively high resolution global LSM, and also the pitfalls of trying to validate such a model using point data. One might conclude, based on comparison with one or more in situ time series, that a model is doing a good, fair, or poor job, and such is the case with Fig. 6g.

Figures 6h (northwestern Indiana), 6i (northwestern Virginia), and 6j (central New Jersey) present comparisons at three locations in the eastern United States. In general, the two simulations correspond fairly well to the observations. One might conclude that the updating scheme produced a moderate improvement, especially in Fig. 6h. The observations in Figs. 6h and 6j further emphasize the subpixel variability of snow water storage. In Fig. 6i, the temporal fidelity of the model output is impressive, but it appears to overestimate the snow water equivalent that resulted from the 16 February storm by about 30 mm, or 100%–300%. It would have been useful to have a better sampling of ground measurements in order to make a fair judgment of the model (and/or precipitation forcing).

To gain a better understanding of the broad-scale effects of the updating scheme, time series of modeled output and Co-op network observations were averaged over three regions: eastern Montana, Midwest, and mid-Atlantic (Fig. 7). These regions were chosen because they included areas where the updated and control simulations showed significant differences and also because they had a reasonably even distribution of observation stations. Mountainous regions in the western United States were not included because seasonal snow cover was continuous during the period of study, and therefore the updates had no effect in these regions. Consequently, SNOTEL observations were not used.

Figure 8 plots the time series for the three regions. The updated output is consistently closer to the observations than the control. In all cases the updating scheme effected improvements in root-mean-square error, bias, and correlation coefficient (Table 2). However, save for a brief period in January in the Midwest, all improvements are due to a reduction in snow. Had the updates begun in autumn when the first snowfalls occurred, they potentially could have caused increases in snow in more locations, and comparisons in the mountains would have been worthwhile.

5. Discussion

The updating scheme presented here was developed in order to exploit the snow cover information contained in MODIS data, despite its limitations. In particular,

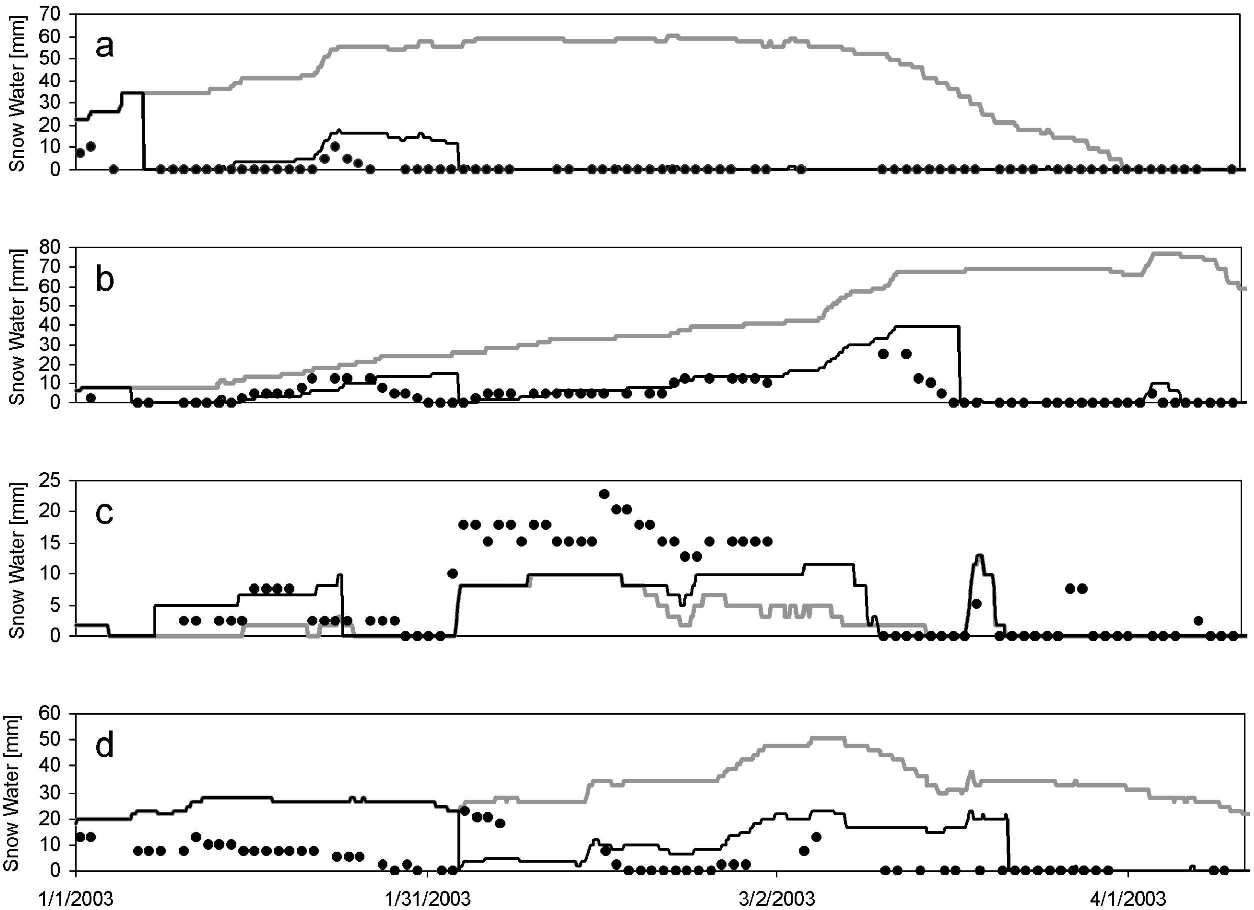

FIG. 6. Time series of snow-water equivalent (mm) from ground-based observations (SNOTEL or Co-op) and GLDAS/Mosaic control (gray line) and assimilation run (black line) outputs. Letters correspond to those in Table 1; circles are first listed station, triangles are second, and diamonds are third.

MODIS cannot resolve snow-depth or -water equivalent, nor can it ''see'' through clouds. However, MODIS may have certain advantages over the Advanced Microwave Scanning Radiometer (AMSR) aboard NASA's *Aqua* satellite, which can be used to estimate snow-water equivalent. First, MODIS is deployed on both *Terra* (launched 18 December 1999) and *Aqua* (launched 4 May 2002), so that the MODIS data have greater coverage and a longer record. Second, the retrieval of snow-water equivalent from AMSR data is complicated by many factors including vegetation, liquid water in the snowpack, and electromagnetic interference. Therefore it is worthwhile to develop techniques to utilize both types of observations with the ultimate goal of producing a single model-assimilated product.

TABLE 2. Statistics of comparison of regional-average time series of modeled, assimilated, and observed snow-water equivalent. Relative bias was calculated as the mean bias over the mean observed snow water equivalent over the time period.

Region and simulation	Rms error (mm)	Mean bias (mm)	Relative bias (%)	Correlation coefficient
Eastern Montana control	30.5	26.2	350	0.11
Eastern Montana updated	6.3	3.2	43	0.58
Midwest control	3.1	2.2	106	0.63
Midwest updated	1.4	0.0	0	0.83
Mid-Atlantic control	15.0	13.9	320	0.75
Mid-Atlantic updated	8.0	5.5	126	0.81

The results demonstrate that the updating scheme skillfully removes superfluous modeled snow, but that it results in an increase in snow much less frequently. This may be due in part to the fact that the updates began on 1 January, well after the start of northern winter. If updates had begun in the previous autumn, snow added to some areas might have provided a base to allow subsequent snowfall to accumulate, and the increased (relative to the control) snow amounts might have persisted through to the spring. Ineffectiveness of the scheme in adding snow is also attributed to the thinness of the added snow layer, 5-mm water equivalent, which melts away quickly if the forcing near surface air temperature is much above freezing. Adding even a

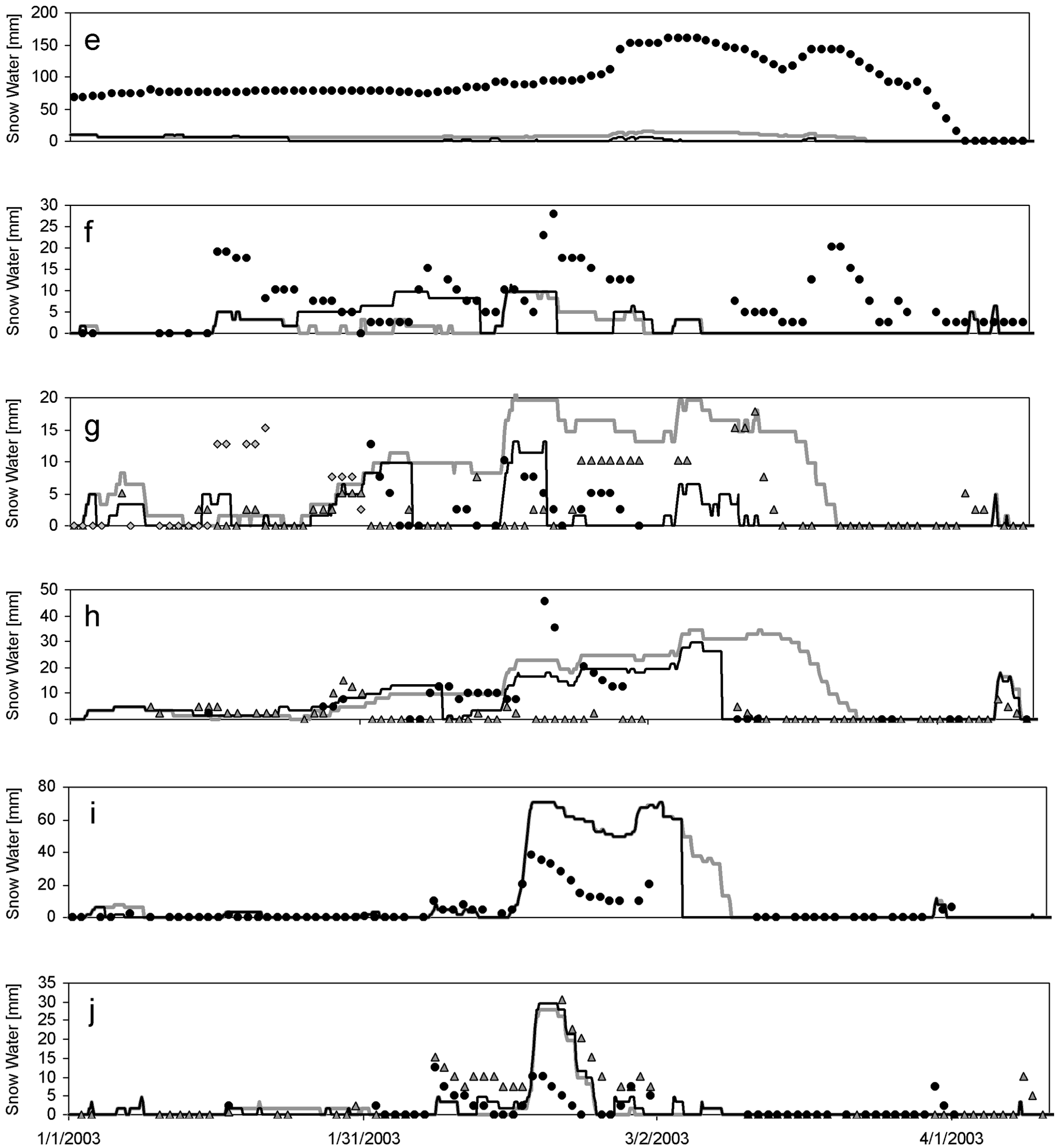

FIG. 6. (*Continued*)

thin layer of snow can have important consequences for the simulated energy balance because snow has a high albedo. However, in the case of Mosaic, 5 mm is the minimum amount of snow that can modify albedo, so that any melting eliminates that effect. The thickness of the added layer can easily be increased in this updating scheme, but the difficulty in adding snow might also be handled more cleverly, as described below.

Data assimilation may have deleterious effects on other water and/or energy processes when the data assimilation fluxes are large. This is one reason for adding only a thin layer of snow. The data assimilation fluxes can be especially detrimental if snow is added and immediately melts day after day, in a location where MODIS identifies snow but the model prevents snow from remaining. For example, snow was added to the model

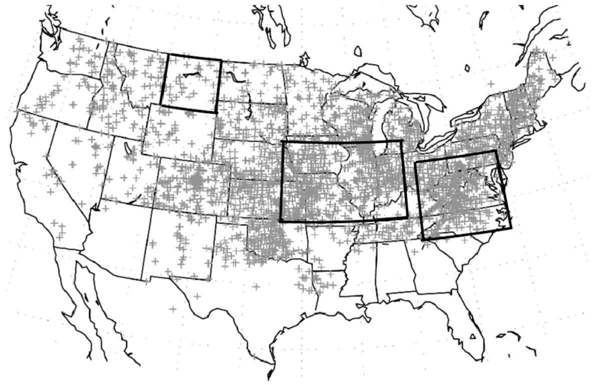

FIG. 7. Averaging regions (black boxes), from west to east: eastern Montana, Midwest, and central Atlantic. Gray crosses indicate locations of cooperative network sites that reported at least once during the period of study.

grid cell containing Baldy Peak in west-central Arizona 45 times during the 101-day simulation, which would have been equivalent to a more than 20-cm increase in precipitation. The explanation is that Baldy Peak is not resolved at the resolution of the GEOS input ($1° \times 1.25°$), so that the forcing air temperature, which is an average meant to represent Baldy Peak and the surrounding area of Arizona, is too high to sustain snow. Snow was added to individual grid cells (at least one subgrid tile) 108 184 times during the 101-day simulation, and on 21 700 of those occasions snow was added to the same grid cell again the following day. From these numbers and with several implicit assumptions, it is estimated that snow added by the updating scheme is melted by the model immediately and erroneously about 20% of the time.

A more sophisticated updating scheme should attempt to minimize these assimilation fluxes. One approach would be to develop a multivariate snow assimilation scheme, thus incorporating observations of snow-water equivalent (as from AMSR) as well as other land surface states whose bias adversely interacts with the snow states (i.e., surface temperature). However, a surface temperature constraint would have to be applied continuously because soil temperature has little inertia. Tests (not presented here) showed that simply adjusting the surface temperature to freezing whenever snow was added did not influence the persistence of snow cover appreciably. Adjusting the near-surface air temperature forcing might be more effective. Another potential solution is to couple an atmospheric boundary layer model to the land surface model to enable feedbacks between the updated snow state and the atmosphere, possibly resolving the air temperature–related problems. It is also recommended that future updating schemes take advantage of the high resolution of MODIS observations. This could be accomplished by variably adjusting the snow-water equivalent based on the percentage of snow cover in the MODIS observation, or by updating the model's representation of subgrid snow coverage, if it exists. Finally, a snow-impossible mask that varies with time would also improve the results.

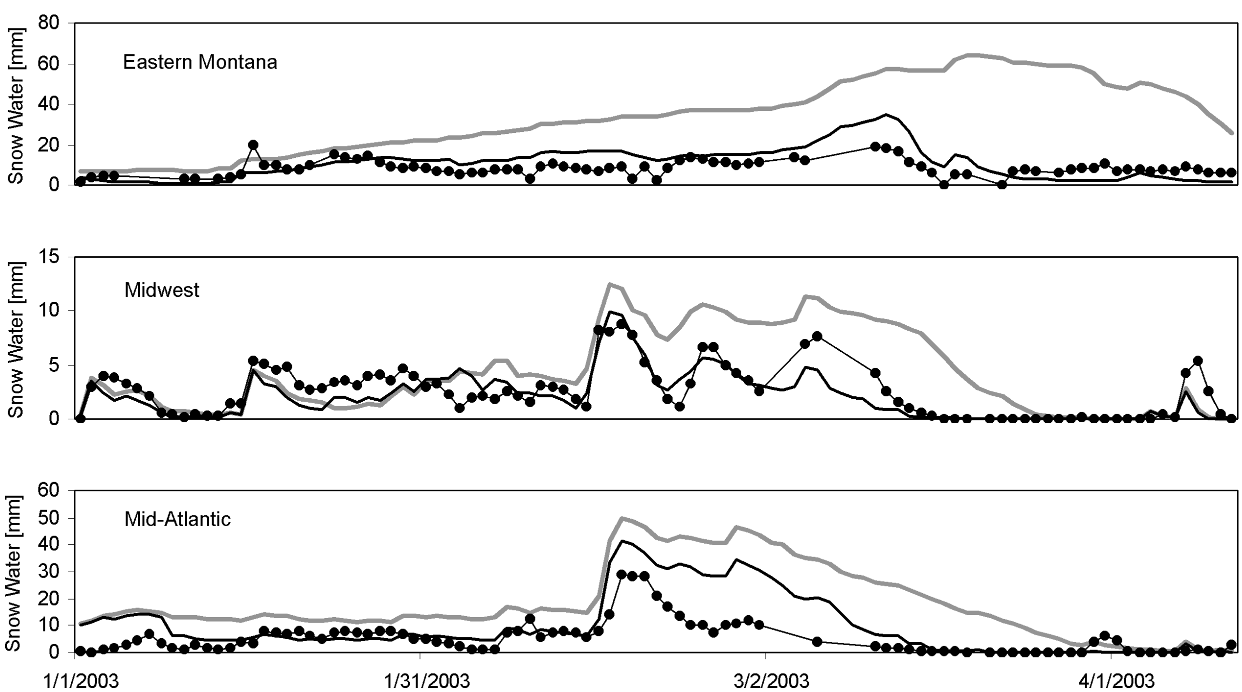

FIG. 8. Regional-average time series of snow-water equivalent (mm) from Co-op ground-based observations (black dots) and GLDAS/Mosaic control (gray line) and assimilation run (black line) outputs.

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